An approach to the use of hydrogen for commercial aircraft engines

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Abstract: This paper presents some results on the performance of hydrogen-based engines. In particular, the following aspects are addressed: benefits associated with specific fuel and energy consumption, net thrust, turbine entry temperature, and hardware changes needed in the upgrading process from kerosene to hydrogen. Hydrogen is a high-energy clean-burning fuel whose main combustion product is water vapour plus traces of nitrogen oxides. This fact suggests that, provided that the technology is available, the use of hydrogen could offer some opportunities for the environmentally friendly development and sustained growth of commercial aviation. The study has been performed in the frame of the Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE) project. This is a Fifth Framework Programme, supported by the European Commission, whose objective was to assess the feasibility of using hydrogen as a clean energy source for air transportation systems.

Keywords: hydrogen, aeroengine, aircraft engine, performance, heat exchanger, alternative fuels

1 INTRODUCTION

Provided that the technology is available, the use of hydrogen for commercial aircraft engine applications might offer some future opportunities to attain an environmentally friendly growth in the air transportation business. Also, there is a need to limit our reliance on fossil fuels whose supply may be hampered either because resources run out, or by geostrategic or environmental reasons. The subject is, of course, not new since the first in-depth studies in this field, which date back to the 1970s, were performed as a consequence of the petroleum crisis [**1–4**]. Specific topics such as aircraft configuration and its influence on aircraft aerodynamics, and safety aspects have been dealt with in references [**5**] and [**6**] respectively, while a comprehensive review of the field can be found in reference [**7**].

Nevertheless, most publications found in the literature are devoted to the use of hydrogen as a ground transportation fuel. Some of these [**8, 9**] address the economic, technical, environmental, and political implications of its implementation, while others focus either on specific technical problems [**10, 11**] or on hydrogen production [**12–16**].

One important topic, which is not always properly considered because it is difficult to estimate [**8, 9**], is the environmental impact of the hydrogen manufacturing process. The fact that some of these processes produce significant pollutant emissions and use fossils [**12–16**] suggests that renewable energy sources should be implemented in the overall scheme.

Recently, the use of hydrogen as an alternative fuel is emphasized for three reasons: the need to save fossil resources, the drive towards minimization of the impact associated with the eventual drying out of those very resources, and, last but not least, the necessity to control pollutant emissions. In this context, the Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE) project [**17, 18**] is an European programme, supported by the European Commission (EC) within the Fifth Framework Programme, which was devoted to studying the use of hydrogen as a future air transportation fuel to be implemented within 50 years. The project was carried out by 36 partners from 11 European countries and it covered relevant technical, environmental, and strategic aspects needed to initiate larger-scale research and development activity. Specifically, it covers the following aspects: aircraft configuration, system architecture and sizing, availability of and requirements for components, propulsion system, safety aspects, environmental impact with specific emphasis upon contrails formation or water vapour effects, and fuel sources and infrastructure at airports [**17–19**]. In parallel, there are some other programmes addressing the issues of ground transportation and power generation [**20, 21**].

This paper deals with the study of the modifications to be implemented on a conventional engine, to burn hydrogen, while keeping the hardware changes to a minimum as well as with its possible benefits [**17, 22, 23**]. In this regard, unconventional propulsion system is not considered. Regarding the paper structure, a discussion on gas properties, performance hypothesis, and modifications to be implemented on a commercial computer code to allow for hydrogen-fuelled engine simulation is presented first. In particular, the code structure was changed to allow for the insertion of a heat exchanger (HE) at different aerodynamic engine sections whose objective is to heat hydrogen from the fuel tank temperature to injection conditions. The particular HE location in the engine cycle gives raise to different engine configurations, and two of these were studied in depth: an external HE and an HE located in the jet pipe at the low-pressure turbine (LPT) exit. In the second part of the paper, three commercial turbofans plus a turboprop, covering aircraft needs from regional to long range, were studied. Also, engines running with the same thrust or with the same turbine entry temperature (TET) for both fuels, namely kerosene and hydrogen, were also considered. Finally, hardware changes and conclusions are presented.

2 SIMULATION METHODOLOGY

A discussion on the methodology used for engine performance simulation when burning hydrogen is presented in this section. The GasTurb [**24**] commercial code was used for engine simulation, on which modifications were implemented as customary to achieve the objectives of this study and as a consequence of the discussion contained in the next few sections. The code where these modifications have been implemented will be referred to as the modified code. This discussion includes four topics:

(a) calculation of the gas properties;
(b) calculation of thermodynamic variables at the main burner exit;
(c) the HE insertion in the engine cycle;
(d) code validation.

2.1 Gas properties

Gas properties for mixtures of air and kerosene, and of air and hydrogen were evaluated first, the objective being to use the same engine simulation methodology for design and off-design conditions, and for both fuels. In particular, two extreme cases were accounted for.

Case 1: *Complete combustion.* Product species are CO_2, H_2O, N_2, Ar, C, and O_2.

Case 2: *Equilibrium conditions.* In this case, the product composition corresponds to the equilibrium composition for a given temperature, fuel-to-air ratio, and pressure.

Aiming to assess whether some simplifications could be implemented in the commercial code, the products thermodynamic characteristics were computed for different temperatures and typical fuel-to-air ratios (FARs). To compute these variables in the case of complete combustion, the continuity and conservation equations were used while, for equilibrium conditions, the methodology of reference [**25**] was followed through. In both cases, species thermodynamic characteristics were taken from reference [**26**]. Table 1 shows the influence of temperature on some thermodynamic variables when kerosene is used and, in the same fashion, this table also shows similar figures when hydrogen is used as the engine fuel. Pressure, which could have a broad variation in aircraft engines, is not included in Table 1 because its influence is negligible for low FARs that are precisely the case for subsonic aircraft engines.

Table 1 Comparison of gas properties for cases 1) and 2), and for typical FARs. $\Delta = |(\text{case 2} - \text{case 1})/\text{case 2}|$

Fuels	Properties				
	Temperature (K)	Δh or ΔT (%)	C_p (%)	γ (%)	ΔS (%)
Kerosene	1100	0	0	0	0
	1500	<1.5	<1.5	<0.5	<1.5
	1700	<2.5	<3	<1	<2.5
Hydrogen	1100	0	0	0	0
	1500	<1.5	<1.5	<0.5	<1.5
	1700	<2.0	<3.5	<1	<2.0

The results presented in Table 1 show that differences start to be significant above 1100 K. This means, as could be expected, that case 1 should not be used for high temperatures. The reason is that, at those temperatures, the complete combustion hypothesis leads to a product composition that is far off the actual chemical equilibrium conditions (case 2). That is, mixing and recirculating processes inside the combustion chamber make sure that residence time of the fluid particles is much longer than the chemical reaction time (Damkohler $\gg 1$); then it is justified to assume a chemical equilibrium state inside this component. The approach that has been implemented for engine cycle computations has been to use complete combustion everywhere except at the burner, where equilibrium conditions were enforced. This patching approach presents the advantage of minimizing changes in the code while retaining the most important physics aspects, so that overall code accuracy is not compromised.

2.2 Main burner calculation

The burner exit enthalpy, assuming adiabatic combustion, is obtained from the energy equation

$$h_{\mathrm{p}}(T_{\mathrm{p}}) = \frac{h_{\mathrm{in}}(T_{\mathrm{in}}) + \mathrm{FAR}\, h_{\mathrm{fuel}}(T_{\mathrm{inj}})}{1 + \mathrm{FAR}} \tag{1}$$

where $h_{\mathrm{p}}(T_{\mathrm{p}})$ is the enthalpy at the burner exit, h_{in} (T_{in}) the enthalpy at the burner entrance, FAR the fuel-to-air ratio at the burner, and $h_{\mathrm{fuel}}(T_{\mathrm{inj}})$ the fuel enthalpy at the injection temperature T_{inj}. h_{fuel} (T_{inj}) is influenced by the fuel temperature, which could be important when burning hydrogen. The enthalpy h_{fuel} (T_{inj}) is given by

$$h_{\mathrm{fuel}}(T_{\mathrm{inj}}) = h_{\mathrm{fuel}}(298.15) + \Delta h_{\mathrm{fuel}}\Big|_{298.15}^{T_{\mathrm{inj}}} \tag{2}$$

where $h_{\mathrm{fuel}}(298.15)$ could be computed, from the definition of the lower heating value (LHV), as

$$h_{\mathrm{fuel}}(298.15) = \frac{1 + \mathrm{FAR}_{\mathrm{stoich}}}{\mathrm{FAR}_{\mathrm{stoich}}} h_{\mathrm{p}}(298.15) + \mathrm{LHV} - \frac{h_{\mathrm{air}}(298.15)}{\mathrm{FAR}_{\mathrm{stoich}}} \tag{3}$$

where $\mathrm{FAR}_{\mathrm{stoich}}$ is the FAR for a stoichiometric mixture, h_{air} (298.15) is the enthalpy of air, and h_{p} (298.15) represents the enthalpy of products for stoichiometric mixtures of fuel and air at 298.15 K, and water in the gas state. The hydrogen properties were taken from reference [**26**] for hydrogen temperatures above 200 K and from reference [**27**] for temperatures below 200 K. These expressions allow for the calculation of the enthalpy at the main burner exit and also provide the influence of fuel temperature at injection conditions and the influence of the LHV on engine performance. In particular, 43.1 MJ/kg and 120 MJ/kg were the assigned LHV values for kerosene and hydrogen respectively.

2.3 Heat exchanger

The implementation of an HE, at different engine sections, has two basic objectives which have to be accomplished bearing in mind the drive to keep engine changes to a minimum [**17, 23**]. The first objective is to inject hydrogen in a gaseous state, and the second aims to improve the specific fuel consumption (SFC) [**7, 23, 28**]. The HE is needed because the fuel control system requires liquid hydrogen to be heated to temperatures between 150 K and 250 K prior to injection.

The HE is simulated in the code by including an enthalpy drop and a stagnation pressure drop in the mainstream; in some cases a bleed stream from the engine is also considered. The enthalpy drop, Δh_{m}, is the enthalpy decrease needed to heat hydrogen from the fuel tank temperature to the fuel temperature at injection section, i.e. Δh_{fuel}, affected by dissipation effects which are represented by a HE efficiency. The enthalpy drop could be modelled including the heat exchanger efficiency η_{He} as [**22, 23**]

$$\Delta h_{\mathrm{m}} = \frac{\Delta h_{\mathrm{fuel}}}{\eta_{\mathrm{He}}} \tag{4}$$

2.4 Validation

The original and modified codes were validated by using engine public data of a typical V2500 kerosene-based engine series and results from other project partners codes; a flow chart including the whole process is presented in Fig. 1. The results obtained showed that both codes could be used with confidence for conventional engines burning kerosene. Because hydrogen-based engine data are not available, all results have been obtained assuming that the modified code is still acceptable when using hydrogen.

3 ENGINE RESULTS

Regarding engine selection, the idea was to cover the needs of different aircraft sizes and ranges. In particular, four engines were identified to that end: BRR710-48, V2527A5, Trent 884, and the PW120 turboprop. Table 2 shows the main characteristics of those engines.

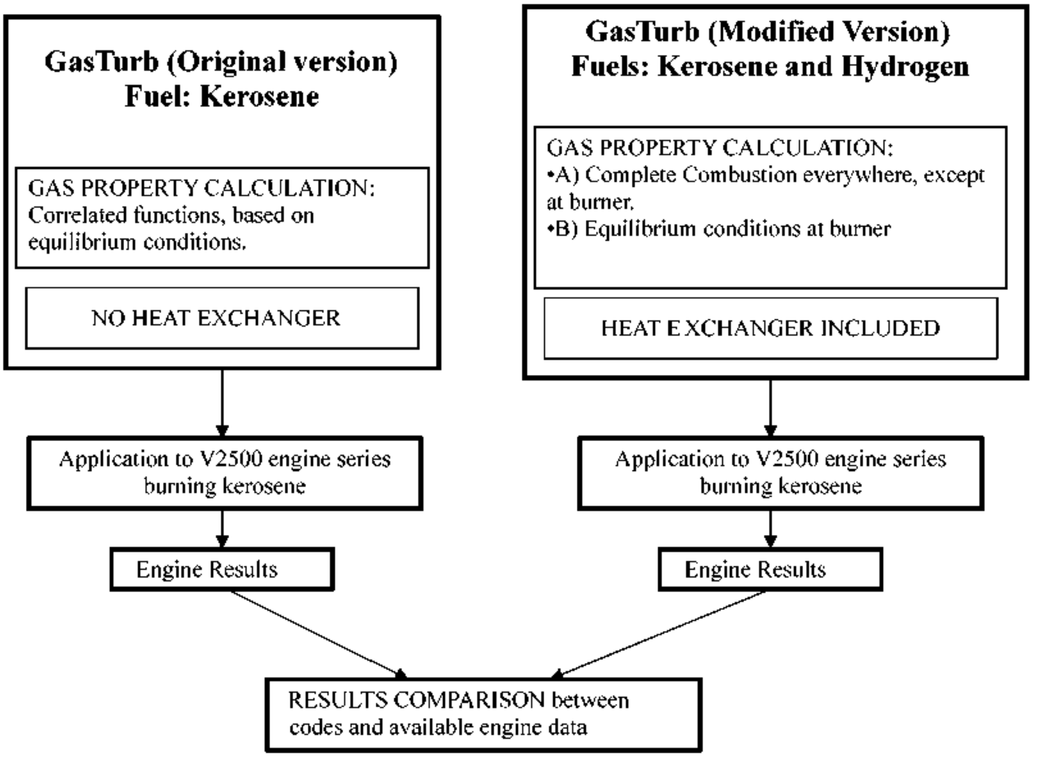

Fig. 1 Flow chart for validation of original and modified codes

3.1 Engine model

The engine models for each of the four chosen engines were generated using published data, data from other CRYOPLANE project partners, and design data for the different components. For turbomachinery, standard modern maps were used for off-design performance calculation after performing the appropriate scaling.

For kerosene-based engines, the design point was fixed at sea level static (SLS) adjusting component efficiencies to match net thrust F_n and SFC. Then, the off-design calculation provides the net thrust and SFC at cruise conditions, given in Table 3. Normally, cruise performances are close to the known data. However, when this was not the case, the efficiency of components at SLS was adjusted. The model validation, in both conditions, is important, firstly, to ensure correct results in all flight conditions and, secondly, because most of the fuel is consumed in these flight conditions. In cruise conditions the engine runs at a required thrust, its value being taken from the known data.

Table 2 Characteristics. of main engines (ISA, international standard atmosphere; SLS, sea level static; OPR, overall pressure ratio; OFPR, outer fan pressure ratio; BPR, bypass ratio; ESHP, equivalent staff horsepower)

	Value for following engines			
	BR710-48	V2527A5	Trent 884	PW120
Flight conditions	SLS ISA+20 C	SLS ISA+10 C	SLS ISA	SLS ISA+28 C
OPR	24	28.5	38.8	11.4
OFPR	1.70	1.70	1.7	
BPR	4.2	4.8	5.9	
Length (mm)	3409	3200	4369	2130
Diameter (mm)	1219	1612	2974	640
Weight (kg)	1633	2370	5942	423
F_n (kN)	68.28	117.78	384.8	
ESHP (kW)				1465.99
SFC (g/kN s)	11.29	9.64	9.31	
SFC (g/kW h)				295.42
Inlet air flow (kg/s)	197	355.6	1174.8	6.7

Table 3 Engine data for BR710-48 (baseline engine), when burning kerosene or hydrogen (SLS ISA + 20C; OPR, 24; OFPR, 1.70; BPR, 4.2; length, 3409 mm; diameter, 1219 mm; mass, 1633 kg). The engines are running at the same thrust, and there is an external HE when using hydrogen ($T_{fuel} = 250$ K)

	Value			
	SLS, ISA+10C		Cruise (11 km, $M_0 = 0.8$), ISA	
	Kerosene	Hydrogen	Kerosene	Hydrogen
F_n (kN)	66.28	66.28	8.67	8.67
SFC (g/kN s)	11.273	3.979	17.910	6.365
W_2 (kg/s)	197.00	197.00	70.16	70.11
W_{fuel} (kg/s)	0.747	0.264	0.155	0.055
TET (K)	1507.9	1470.9	1103.7	1089.5
SEC (kJ/kN s)	485.88	477.46	772.02	763.81
SFC_{CH}/SFC_{H_2}	2.833		2.814	
SEC_{CH}/SEC_{H_2}	1.018		1.011	
$(SFC_{CH} - SFC_{H_2})/SFC_{CH}$ (%)	64.71		64.71	
$(W_{fuel\ CH} - W_{fuel\ H_2})/W_{fuel\ CH}$ (%)	64.71		64.71	
$(SEC_{CH} - SEC_{H_2})/SEC_{CH}$ (%)	1.73		1.06	

For hydrogen, the design point was also fixed at SLS. All engine characteristics (component efficiencies, compressors pressure ratio, BPR ratio, etc) were kept, but it was considered that fuel temperature at the injection section was in the range 150–250 K. Regarding the engine rating, two different cases were considered.

Case a. The engine runs at the same SLS net thrust as the engine when burning kerosene.

Case b. The engine runs at the same SLS TET as the engine when burning kerosene.

Cases a and b will be referred to in the next few sections as designs for the same net thrust or the same TET respectively. The influence of both the HE location and the fuel temperature, which are not fixed at this stage, will be addressed in sections 3.2 and 3.3 respectively.

3.2 Engine configurations

Implementing a heat exchanger implies that different configurations may arise. In particular three possibilities were considered.

1. The HE is placed in the mainstream. Then, all mainstream gases go through the HE.
2. The HE is placed right out of the mainstream. Then, a bled flow from the mainstream goes through the HE and returns to the mainstream at a further downstream section.
3. The HE is placed right out of the engine and is fed by an external aerodynamic stream.

In the first option, the HE is placed in the mainstream at the LPT exit in the jet pipe before the exhaust nozzle, where the temperature is high enough to allow for a fairly small HE. In this case the HE could simply be a coil tube winding all over the inside face of the jet pipe casing, having a weight increase less than 1 per cent [**19**]. This option was addressed in reference [**7**] and will be referred to hereafter as the HE at the LPT exit. The HE at the fan exit was not considered because of the low mainstream temperature. Nevertheless, this stream could be linked with the mainstream at the LPT exit to control the hydrogen injection temperature. Locating the HE at the engine inlet was dismissed because of potential safety problems.

In the second option, three alternatives were considered.

i. The air is bled at the intermediate-pressure compressor exit and returned to the mainstream at the LPT exit.
ii. The air is bled from the high-pressure compressor exit and returned to the mainstream at the LPT exit.
iii. Cooling air from nozzle guide vanes is used to heat the hydrogen fuel to the required temperature, which will meet the fuel control system constraints but there are no benefits whatsoever for the SFC at constant TET.

Alternatives (i) and (ii) were rejected because of the high pressure losses that may hamper engine performance and also because of changes in turbine flow capacities which could generate important hardware changes. Alternative (iii), which could allow a significant increase in TET, was assigned within the CRYOPLANE project to the studies of unconventional engines.

The third option is promising and will be referred to hereafter as the external HE. The external aerodynamic air stream is used to heat the hydrogen so that no energy is sucked out of the engine cycle. However, in this case, the HE size and location outside of engine casing may well pose a relevant problem. In any case, the major aircraft configuration changes are related to the new fuel tank configuration to store liquid hydrogen; these changes give rise to a larger and weightier aircraft [**5–7**, **19**].

As a consequence, only two configurations, namely the HE at the LPT exit and the external HE, have been studied in depth.

3.3 Influence of fuel temperature

Figures of merit to assess fuel temperature influence were SFC and TET for engines running at the same net thrust, and SFC and net thrust (F_n) for engines running at the same TET. Now, the fuel temperature is the only free parameter whose influence will be studied hereafter. The study was carried out for the four engines under consideration and, since similar conclusions were found, only those results corresponding to the BR710-48 turbofan engine are presented.

Figures 2 and 3 show the results for the case of same net thrust and external HE, while Figs 4 and 5 present the equivalent results for the case of the same net thrust and the HE at the LPT exit. From Figs 2 and 4, an interesting increase in the SFC can be appreciated; this increase is 1.7 per cent in the case of the HE at the LPT exit and above 2.5 per cent in the case of the external HE, when the fuel temperature increases from 25 K to 250 K. The drawback could be that it produces a small increase, from 2 to 5 K, in the TET depending on the engine configuration (see Figs 3 and 5). Note that an increase in TET of 10 K represents a thrust increase of the order of 2 per cent, and a decrease on turbine life in 25 per cent.

Figures 6 and 7 present particular results for constant TET and the HE at the LPT exit, instead of constant net thrust. These configurations give high increases in SFC when compared with reference conditions but they produce a similar percentage of net thrust loss.

Both configurations, the external HE and the HE at the LPT exit, produce similar increases in SFC from the viewpoint of the fuel temperature influence. The differences consist of a small increase in TET for the same thrust or a small decrease in thrust for the same TET as well as significant differences in heat exchanger weight and size. In the project, it was considered more interesting to keep the thrust and a small HE size, since new aircraft configurations will need an extra thrust when using hydrogen [**5**, **7**, **17**].

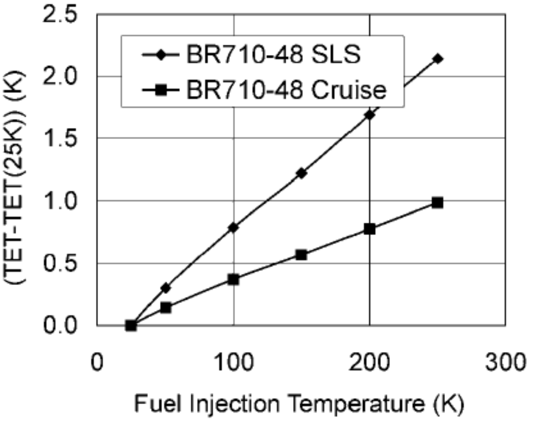

Fig. 3 Influence of the fuel injection temperature on the TET when it is compared with the TET for $T_{\text{fuel}} = 25$ K. The engine is always running at the same net thrust for both fuels, and there is an external HE

3.4 Global performance results

Previous sections have showed the benefits and the convenience of increasing the fuel temperature.

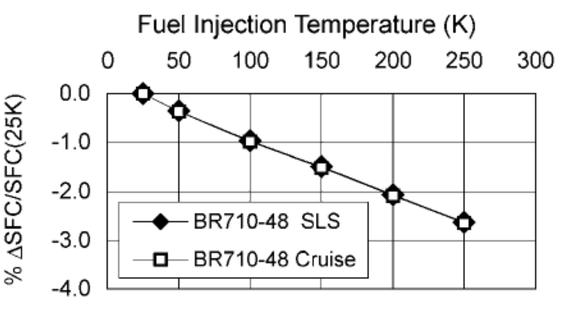

Fig. 2 Influence of the fuel injection temperature on the SFC when it is compared with the SFC for $T_{\text{fuel}} = 25$ K. The engine is always running at the same net thrust for both fuels, and there is an external HE

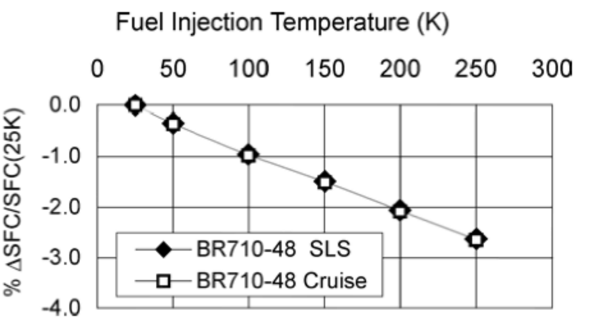

Fig. 4 Influence of the fuel injection temperature on the SFC when it is compared with the SFC for $T_{\text{fuel}} = 25$ K. The engine is always running at the same net thrust, and there is an HE at the LPT exit

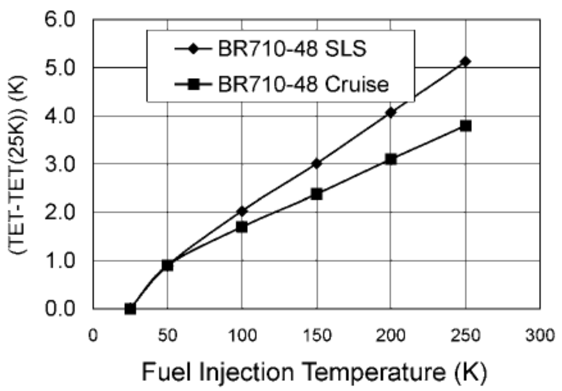

Fig. 5 Influence of the fuel injection temperature on the TET when it is compared with the TET for $T_{fuel} = 25$ K. The engine is always running at the same net thrust, HE at the LPT exit

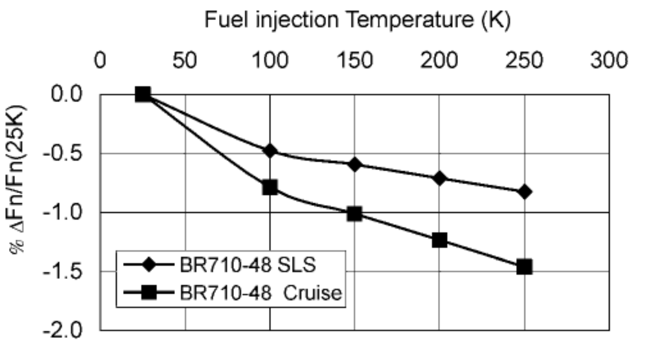

Fig. 7 Influence of the fuel injection temperature on the net thrust, when it is compared with the net thrust for $T_{fuel} = 25$ K. The engine is always running at the same TET, and there is an HE at the LPT exit

Now, this section presents some global results for different feasible design options for hydrogen-based engines, with a fixed fuel temperature $T_{fuel} = 250$ K, as well as their comparison with the kerosene engine. Table 3 presents the results for the BR710-48 engine where both designs, kerosene and hydrogen, correspond to engines running at the same net thrust, and with an external HE when burning hydrogen. This hydrogen-based engine design is referred to as the baseline engine or reference for comparison with the other options.

Some conclusions can be gathered from the results presented in Table 3.

1. At SLS the engine runs at 37 K lower than the TET when burning hydrogen. This fact suggests that a very important increase in engine life could be achieved. Note that this TET decrease means that the turbine life almost doubles.
2. The SFC is much lower when burning hydrogen, by a factor of nearly 3. This translates into a significant fuel mass saving. However, the density of kerosene is roughly four times that of hydrogen; so the need to have large and insulated storage tanks may offset the benefits associated with improving the SFC and this may raise the question of increasing fuel temperature [**5–7**, **18**, **19**].
3. The specific energy consumption (SEC) improves by a shade more than 1 per cent. This improvement is caused by fuel property changes when burning hydrogen.

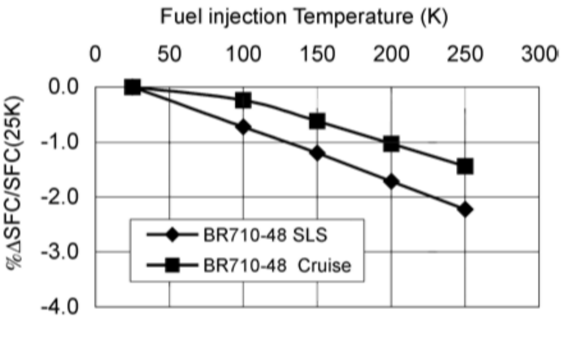

Fig. 6 Influence of the fuel injection temperature on the SFC when it is compared with SFC for $T_{fuel} = 25$ K. The engine is always running at the same TET, and there is an HE at the LPT exit

Besides the baseline engine, there are other options for a hydrogen-based engine, using the concept of the same net thrust or the same TET, and HE location. Tables 4 and 5 show some significant results for specific designs and their comparison with the baseline engine and kerosene engine. The selection of the best hydrogen-based engine could be driven by different figures of merit (low SFC; low TET to increase engine life; higher thrust; even the HE weight and size) and their effects on the whole system and, specifically, on aircraft configuration.

Table 4 Engine data comparison, for BR710-48 burning hydrogen ($T_{fuel} = 250$ K) and for the different design options

		Value for following design options	
	Flight conditions	Baseline engine $F_{n\,H_2} = F_{n\,CH}$	$F_{n\,H_2} = F_{n\,CH}$, HE at LPT exit
F_n (%)	Sea level	0	0
SFC (%)	Sea level	0	+0.972
TET (K)	Sea level	1470.9	1476.4
SEC (%)	Sea level	0	+0.955
F_n (%)	Cruise	0	0
SFC (%)	Cruise	0	+0.946
SEC (%)	Cruise	0	1.07
TET (K)	Cruise	1089.5	1093.8
SFC_{CH}/SFC_{H_2}	Sea level	2.883	2.806
SEC_{CH}/SEC_{H_2}	Sea level	1.018	1.008
SFC_{CH}/SFC_{H2}	Cruise	2.814	2.785
SEC_{CH}/SEC_{H_2}	Cruise	1.011	1.000

Table 5 Engine data comparison for BR710-48 burning hydrogen ($T_{\text{fuel}} = 250$ K) and for the different design options

	Flight conditions	Value for following design options: $\text{TET}_{\text{H}_2} = \text{TET}_{\text{CH}}$	$\text{TET}_{\text{H}_2} = \text{TET}_{\text{CH}}$, HE at LPT exit
F_n (%)	Sea level	+3.938	+3.304
SFC (%)	Sea level	+2.544	+3.179
SEC (%)	Sea level	+2.791	+3.208
TET (K)	Sea level	1507.9	1507.9
F_n (%)	Cruise	+2.42	+1.15
SFC (%)	Cruise	−0.503	+0.744
SEC (%)	Cruise	−0.518	+0.772
TET (K)	Cruise	1103.7	1103.7
$\text{SFC}_{\text{CH}}/\text{SFC}_{\text{H}_2}$	Sea level	2.763	2.746
$\text{SEC}_{\text{CH}}/\text{SEC}_{\text{H}_2}$	Sea level	0.990	0.986
$\text{SFC}_{\text{CH}}/\text{SFC}_{\text{H}_2}$	Cruise	2.828	2.793
$\text{SEC}_{\text{CH}}/\text{SEC}_{\text{H2}}$	Cruise	1.016	1.003

From Tables 4 and 5 and when the different options are compared with the baseline engine, it can be appreciated that the HE at the LPT exit means lower increases in SFC and SEC, a lower net thrust, and a fairly small HE while a constant TET translates into an increase in net thrust, lower increases in SFC and SEC, and no increase in engine life for the different options.

In the project, the concept of the same net thrust and HE at the LPT exit ($F_{n\,\text{H}_2} = F_{n\,\text{CH}}$ and HE in Table 4) was considered as the most interesting because the whole engine forms a single unit having a small HE. In this case a very important increase in engine life could be obtained: $\Delta\text{TET} = -31.5$ K.

4 ENGINE MATCHING CONSIDERATIONS

Different options have been considered to evolve conventional engines from kerosene to hydrogen. These different designs resulted in different standard corrected flows for turbines, and this means that the section areas might have to be changed to allow for an effective engine matching. The effective minimum cross-section turbine nozzle areas have been estimated assuming a choked turbine nozzle at design conditions; a choked turbine nozzle means that the mass flowrate, effective minimum cross-section area, and stagnation conditions are linked by the expression [**29**]

$$A = \sqrt{\frac{R}{\gamma}}\left(\frac{\gamma+1}{2}\right)^{\gamma+1/2(\gamma-1)}\frac{W\sqrt{T_s}}{P_s} \qquad (5)$$

Table 6 shows the estimated effective minimum cross-sectional turbine nozzle areas for the three turbofans under consideration. Estimated decreases are about 0.5 per cent for the HPTs and less than 1.5 per cent for the LPTs. Additionally, the nozzle throat area will have to be modified in the upgrading fuel process; its modification is not shown because of its easy implementation.

Table 6 Estimated areas for both the LPT and the high-pressure turbine (HPT) as well as their relative variation in the upgrading fuel process. All data correspond to the case of design for the same net thrust and the HE at the LPT exit

Engine	Fuel	A_{41} (HPT) (cm^2)	A_{45} (LPT) (cm^2)	ΔA_{41} (%)	ΔA_{45} (%)
BR710-48	Kerosene	160.446	661.761	0	0
BR710-48	Hydrogen	159.622	653.476	−0.51	−1.25
V2527A5	Kerosene	212.394	686.539	0	0
V2527A5	Hydrogen	211.412	678.817	−0.46	−1.12
Trent 884	Kerosene	445.171	1026.235	0	0
Trent 884	Hydrogen	442.775	1011.527	−0.53	−1.43

5 CONCLUSIONS

1. Regarding the fuels under consideration, there is a large mass saving associated with the use of hydrogen because a 64.7 per cent reduction in SFC; the lower density of hydrogen when compared with kerosene, and its influence on aircraft configuration and performance might offset this mass saving. This may raise the question of increasing fuel temperature.
2. Hydrogen-based engines run cooler than those using kerosene and this fact translates into a significantly longer engine life. The TET decrease is close to 40 K depending on design options.
3. Evolving a conventional engine from burning kerosene to burning hydrogen, without implementing large-scale hardware changes, does not seem to be an insurmountable task. Nevertheless, in-depth studies ought to be put in place. In the end, gains and losses associated with the proposed fuel change need to be investigated in a fully quantitative manner.
4. A different question is the problem of the hydrogen-fuelled aircraft in connection with the whole air transportation scheme. System engineering has its limitations, so, in the end, tilting the balance one way or another might be linked to achieving significant improvements in technology for a final successful development process.

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REFERENCES

1 **Escher, W. J. D.** and **Brewer, G. D.** Hydrogen: make-sense fuel for an American supersonic transport, *J. Aircr*, January 1975, **12**(1), 3–10.

2 **Brewer, G. D., Morris, R. E., Lange, R. H.,** and **Moore, J. W.** Study of the application of hydrogen fuel to long-range subsonic transport aircraft. Report NASA CR-132559, National Aeronautics and Space Administration January 1975.

3 **Brewer, G. D.** and **Morris, R. E.** Study of LH_2 fueled subsonic passenger transport aircraft. Report NASA CR-144935, National Aeronautics and Space Administration June 1976.

4 **Brewer, G. D.** ***et al.*** Final report – study of fueled systems for LH_2 subsonic transport aircraft. Report NASA CR-145319, National Aeronautics and Space Administration December. 1977.

5 **Reshotko, E.** Drag reduction by cooling in hydrogen-fueled aircraft. *J. Aircr.*, September. 1979, **16**(9), 584–590.

6 **Brewer, G. D.** An assessment of the safety of hydrogen-fueled aircraft. *J. Aircr.*, November 1983, **20**(11) 935–939.

7 **Brewer, G. D.** *Hydrogen Aircraft Technology*,1991 (CRC Press, London).

8 **Kreith, F.** and **West, R. E.** Gauging efficiency, well to wheel. *Mech. Engng Power*, June 2003, 20–24.

9 **Berry, G. D., Pasternak, A. D., Rambach, G. D., Ray Smith, J.,** and **Schock, R. N.** Hydrogen as a future transportation fuel. *Energy, Int. J.* April 1996, **21**(4), 289–303.

10 **Sierens, R.** and **Verhelst, S.** Experimental study of a hydrogen-fueled engine. *J. Engng Gas Turbines Power*, January 2001, **123**, 211–216.

11 **Lee, J. T., Kim, Y.Y., Le, C. W.,** and **Caton, J. A.** An investigation of a cause of backfire and its control due to crevice volumes in a hydrogen fueled engine. *J. Engng Gas Turbines Power*, January 2001, **123**, 204–210.

12 **Diver, R. B.** and **Fletcher, E. A.** Hydrogen and oxygen form water III: evaluation of a hybrid process. *Energy, Int. J.*, July. 1980, **5**(7), 597–607.

13 **Diver, R. B.** and **Fletcher, E. A.** Hydrogen and oxygen form water IV: control of an effusional separator during a solar intensity transient. *Energy, Int. J.*, December 1980, **5**(12), 1261–1263.

14 **Block, K., Williams, R. H., Katofsky, R. E.,** and **Hendriks, C. A.** Hydrogen production from natural gas, sequestration of recovered CO_2 in depleted gas wells and enhanced natural gas recovery. *Energy, Int. J.*, February 1997, **22**(2–3), 161–168.

15 **Wallman, P. H., Thorsness, C. B.,** and **Winter, J. D.** Hydrogen production from wastes. *Energy, Int. J.*, April 1998, **23**(4), 271–278.

16 **Tamaura, Y., Steinfeld, A., Kuhn, P.,** and **Eherensberger, K.** Production of solar hydrogen by a novel, 2-step, water-splitting thermochemical cycle. *Energy, The Int. J.*, April 1995, **20**(4), 325–330.

17 Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE), Part B Proposal GRD1-1999-10014, Fifth Framework Programme of the European Communities, Contract G4RD-CT-2000-00192, 14 June 1999.

18 **Klug, H. G.** and **Reinhard, F.** CRYOPLANE: hydrogen fuelled aircraft – status and challenges. *Air&Space Europe*, 2001. **3**(3), 252–254

19 **Westenberger, A.** ***et al.*** Liquid Hydrogen Fuelled Aircraft – System Analysis. Final Technical Report (Published Version), Contract G4RD-CT-2000-00192, Project GRD1-1999-10014. September 2003.

20 **Bannister, R. L., Newby, R. A.,** and **Yang, W. C.** Development of a hydrogen-fueled combustion turbine cycle for power generation. *J. Engng for Gas Turbine Power*, April 1999, **120**, 276–283.

21 **Bannister, R. L., Newby, R. A.,** and **Yang, W. C.** Final report on the development of a hydrogen-fueled combustion turbine cycle for power generation. *J. Engng Gas Turbine Power*, January 1999, **121**, 38–45.

22 **Corchero, G.** Engine data including influence of heat exchanger. Report TTR 4.2-3, Universidad Politécnica de Madrid, Fifth Framework Programme of the European Communities, Contract G4RD-CT-2000-00192, November 2001.

23 **Corchero, G.** and **Montañes, J. L.** Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE). Task 4.2: minimum engine change configurations. Final Report, Universidad Politécnica de Madrid, Fifth Framework Programme of the European Communities, Contract G4RD-CT-2000-00192, November 2001.

24 **Kuzke, J.** *GasTurb 8.0. A Program to Calculate Design and Off-Design Performance of Gas Turbines*, 1999 (Joachim Kurzke, Dachau, Germany).

25 **Gordon, S.** and **McBride, B.** Computer program for calculation of complex chemical equilibrium compositions, rocket performance, incident and reflected shocks, and Chapman–Jouguet detonations. Special Publication NASA SP-275, National Aeronautics and Space Administration, March 1976.

26 **McBride, B. J., Gordon, S.,** and **Reno, M. A.** Coefficients for calculating thermodynamic and transport properties of individual species. Technical Memorandum NASA TM-4513, National Aeronautics and Space Administration October 1993.

27 **Vargaftik, N. B.** Tables on the thermophysical properties of liquids and gases. In *Normal and Dissociated States*, 1975 (Hemisphere, Washington, DC) (John Wiley, New York).

28 **Corchero, G.** and **Montanes, J. L.** An approach to the use of hydrogen in actual commercial aircraft engines. In proceedings of the 16th ISABE International Symposium on *Air Breathing Engines*, Cleveland, Ohio, USA, September 2003, AIAA paper 2003-1187.

29 **Hill, P. G.** and **Peterson, C. R.** *Mechanics and Thermodynamics of Propulsion*, 1965 (Addison-Wesley London).

APPENDIX

Notation

A	section area
BPR	bypass ratio

C_p	specific heat at constant pressure
ESHP	equivalent shaft horsepower
FAR	fuel-to-air ratio
F_n	net thrust
h	enthalpy
HE	heat exchanger
HPT	high-pressure turbine
ISA	international standard atmosphere
LHV	lower heating value
LPT	low-pressure turbine
M_0	flight Mach number
OFPR	outer fan pressure ratio
OPR	overall pressure ratio
P	pressure
R	gas constant
S	entropy
SEC	specific energy consumption
SFC	specific fuel consumption
SLS	sea level static
T	temperature
TET	turbine entry temperature
W	mass flow
γ	specific heat ratio
η	efficiency

Subscripts

air	air
CH	kerosene
fuel,	fuel
H_2	hydrogen
He	heat exchanger
in	burner entry
inj	injection conditions (fuel)
m	mainstream
p	products
s	stagnation condition
stoich	stoichiometric
$2, 41, 45, \ldots$	engine aerodynamic section